

Structure Shocks as a Source of Cosmic Rays in Clusters

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Abstract. Shocks are a ubiquitous consequence of cosmic structure formation, and they play an essential role in heating galaxy cluster media. Virtually all of the gas in clusters has been processed by one or more shocks of at least moderate strength. These are collisionless shocks, so likely sites for diffusive shock acceleration of high energy particles. We have carried out numerical simulations of cosmic structure formation that directly include acceleration and transport of nonthermal protons, as well as primary and secondary electrons. Nonthermal emissions have also been computed from the resulting particle spatial and energy distributions. Here we outline some of our current findings, showing that nonthermal protons may contribute a significant pressure in cluster media, and that expected radio, X-ray and γ -ray emissions from these populations should be important cluster diagnostics.

1. Introduction

At least two lines of reasoning lead us to examine the properties of energetic particle acceleration at structure formation shocks. First, virtually all the gas

in filaments, groups and clusters¹ has at some time passed through one, or more probably, several structure shocks (e.g., Quilis et al 1998; Cen & Ostriker 1999; Miniati et al. 2000). Structure shocks involve very diffuse plasmas, so will be “collisionless”. Thus, they are likely to accelerate high energy particles (call them “cosmic rays” or CRs) through the so-called “diffusive shock acceleration”, provided there is a weak magnetic field present (e.g., Blandford & Eichler 1987). As discussed by Blasi at this meeting and outlined briefly below, clusters should be good reservoirs of CR protons, so that over time they will accumulate, possibly even to a level where they can contribute significantly to the cluster pressure (e.g., Berezhinsky et al 1997). CRs have a softer equation of state than nonrelativistic thermal plasma, but CR protons are effectively immune to nonadiabatic cooling. Consequently, they can change the thermodynamic properties of the ICM. In that event it becomes important to include them in consideration of cluster dynamics, especially in cooling flows (see, e.g., the contribution by Ryu et al in these proceedings).

The second rationale for understanding particle acceleration at structure shocks comes from diffuse nonthermal emissions seen in at least some clusters. The most compelling such evidence, known for some time, is the existence of diffuse cluster radio halos and so-called “radio relic” sources (e.g., Feretti & Giovannini 1996; Feretti 1999). The detailed properties of these two classes of radio source are different in some respects, such as polarization and location inside the clusters, but both involve substantial volumes in their host clusters. The radio halos tend to be centered on the cluster cores and are unpolarized, while the relics are most likely to be found on the perimeters of clusters and can be highly polarized. Both types of radio sources result from synchrotron radiation by substantial populations of \gtrsim GeV electrons.

As discussed at this meeting by Fusco-Femiano, X-ray observations now show convincing evidence for diffuse, nonthermal hard X-ray emission in at least Coma and A2256 (e.g., Rephaeli et al 1999; Fusco-Femiano et al 2000). Again, this implies nonthermal electron populations. Here, however, as discussed by several other speakers at this workshop, the origin of that emission and the energy of the electrons are less certain. If the emission is nonthermal bremsstrahlung the electrons are only a little more energetic than the thermal electrons responsible for the soft X-ray continuum. On the other hand, one of the prime candidates for the hard X-ray excesses is inverse-Compton scattered CMB photons, again involving roughly GeV electrons. So far, the evidence requires only nonthermal electrons, since π^0 decays coming from inelastic p-p collisions have not yet been detected. However, for particle acceleration in normal plasmas we should expect energetic hadrons as well. If the accelerators behave similarly to galactic CR accelerators the energy carried by hadronic CRs is likely to be one to two orders of magnitude greater than for electrons, in fact.

To facilitate what follows it may be useful here to review very quickly the key issue of CR longevity in clusters, since that largely controls the needs for extended accelerators of CRs. First, it has long been noted that electrons responsible for the observed radio halos have such short lifetimes to radiative losses that they cannot possibly fill a cluster from a single point source (e.g., Jaffe 1977).

¹To simplify the discussion below we do not distinguish groups from clusters.

Supposing for example, that the cluster magnetic field is $1\mu\text{G}$, then electrons radiating at 1 GHz have Lorentz factors, $\gamma \sim 2 \times 10^4$. For Lorentz factors above a few hundred the dominant energy losses will come from inverse-Compton scattering in this case (e.g., Sarazin 1999), leading to lifetimes $t_r \sim 4 \times 10^{12} \gamma^{-1}$ yrs, or about 2×10^8 yrs in this case. It is simple to show that if we fix the observed radio frequency at 1 GHz, this is about the maximum lifetime of the relevant radiating electrons against combined inverse-Compton and synchrotron radiation.

Although in free flight relativistic electrons could cross a cluster in a few million years, diffuse radio emissions from the clusters and Faraday rotation through some clusters reveal the clear presence of weak magnetic fields (see the contributions by Feretti, Clarke, and Kronberg at this meeting, for example). The observations point to a tangled, perhaps turbulent field. MHD fluctuations will severely restrict their propagation. As an example consider Bohm diffusion, corresponding to scattering on saturated field fluctuations, so that a particle mean free path approximates the particle gyro radius; that is, $D_B = \frac{1}{3} c r_g$, for relativistic particles. This would allow GeV particles to diffuse less than a kiloparsec in a Hubble time. Bohm diffusion is a limiting case, and advective motions will surely carry CR electrons farther than that by a large factor even in the much smaller radiative lifetime of the electrons. But, the very small range of these electrons remains valid under any reasonable set of circumstances. The main consequence of this result is that CR electrons responsible for observed diffuse cluster radio and probably X-ray and predicted γ -ray emissions must be continuously replenished somehow. The observed hard X-ray luminosity of Coma exceeds $10^{43} \text{ erg s}^{-1}$, placing a lower bound on the replenishment rate in that cluster.

Note as well that hadronic CRs, and protons, in particular, are confined similarly by MHD wave scattering. In that case, on the other hand, radiative losses are negligible up to extremely high energies, as are losses due to inelastic collisions with the CMB and the cluster thermal plasma (e.g., Berezhinsky et al 1997). So, the key consequence is that CR protons below about $10^{15} \text{ eV} = 1 \text{ PeV}$ will be essentially locked to the ICM forever, once they are introduced.

The importance of shock heating to the ICM makes diffusive shock acceleration (DSA) an immediate candidate for production of cluster CRs, since DSA can transfer some tens of percents of the energy dissipated at the shock to the CR population (e.g., Blandford & Eichler 1987). For a typical cluster shock that would correspond to a CR energy input rate $\sim 0.1 \rho u^3 R^2 \sim 10^{45} \text{ erg/sec}$ (e.g., Jones et al 2001). Over a Hubble time this could amount to as much as 10^{63} ergs of CR energy. We emphasize from the start that our aim is not to argue for structure shocks as the only source of diffuse CRs in clusters, but that it is one very likely to be there and to be important. Others have estimated that radio galaxies can contribute a similar CR energy flux (e.g., Enßlin et al 1997). Intense starburst activity during galaxy formation has also been proposed (e.g., Völk et al 1996). Turbulent acceleration in the ICM may also play a significant role, especially as a means to reaccelerate CRs introduced by some other means (e.g., Jaffe 1977; Eilek & Wetherall 1999; Brunetti et al 2001).

In the remainder of this paper we will outline the role of structure shocks in determining the conditions in the ICM, review briefly the relevant properties

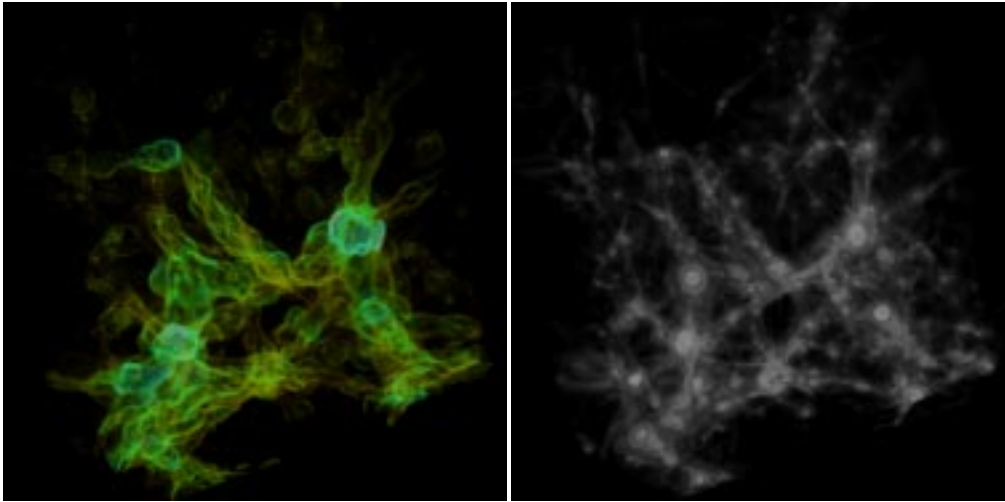


Figure 1. Volume renderings of a $(19h^{-1}Mpc)^3$ portion of a $(75h^{-1}Mpc)^3$ SCDM cosmology simulation showing the locations of clusters and associated shock structures at $z = 0$. Left: Divergence of the baryonic gas flow, or gas compression rate, filtered to show shocks. Right: Bolometric thermal gas emissivity, which peaks in cluster cores. Note the rich web-like character of the shocks often extending deeply into the clusters and twisting along the connecting filaments.

of shock acceleration physics and discuss the results of some numerical simulations of structure formation that include treatment of CR acceleration via DSA, followed by advective transport and relevant energy loss mechanisms. Finally, since the ultimate test of such calculations is their match to observed cluster properties, we have computed “synthetic observations” of nonthermal emissions from simulated clusters, so describe some of those results here, as well. More extensive discussions of most of these issues are contained in our cited works, as well.

2. The Role of Shocks in Cluster Formation

Figure 1 illustrates the rich distribution of shock surfaces that are likely to be associated with large scale structure formation. For reference a volume rendered image of thermal X-ray emissivity is included to help locate clusters. These images are taken from one of our numerical simulations using a grid-based N-body/hydro scheme (Ryu et al 1993). The hydro part of the code uses a “TVD”, Riemann-solver scheme that cleanly captures even relatively weak shocks inside only 2-3 zones, which each span about 100 kpc in the simulation shown. The volume displayed is a little less than $20 h^{-1}Mpc$ on a side at $z = 0$, and was extracted from a full simulation box $75 h^{-1} Mpc$ on a side. For this SCDM model $\Omega_M = 1$, $\Omega_B = 0.13$, $h = 0.5$ and $\sigma_8 = 0.6$, which produces a cluster population at the current epoch consistent with observations.

Structure shocks are most commonly characterized as either “accretion shocks”, if they result from infall of diffuse, intergalactic material onto the

perimeter of a cluster, or “merger shocks” if they result from collision between two clusters. A quick glance at Figure 1 shows that this is an overly simplified picture. For example, collisions between flows in filaments can lead to shocks, and accretion shocks are often hard to distinguish from merger shocks, given the complexity that accompanies the accumulation of mass in regions where clusters are forming. Dissipation at these shocks provides the basic heating of the ICM, although other processes, including feedback from star formation may also be important contributors.

Structure shocks come in a wide range of strengths, most generally indicated by Mach number. That depends especially on the temperature of the inflowing gas, since relative flow velocities tend generally to be of order 10^3 km s^{-1} . To the extent that the interacting material has been virialized the Mach numbers should be small, of course, while cooler material entering a cluster from a filament, for example, may pass through much higher Mach number shocks. Miniati et al (2000) and Miniati (2002a) have examined the histories of shock heating as revealed through cosmological simulations. Integrating over cosmic time they found that moderate strength shocks with Mach numbers roughly in the range $2 \lesssim M \lesssim 7$ contribute most to heating of the ICM. Such shocks are capable of accelerating CRs efficiently, so deserve close scrutiny in that context.

It is important to remember that, since CRs are effectively tied to the ICM up to pretty high energies, the integrated shock history of the ICM determines the character of the CR proton population (as well as their secondary products). So, one would not expect CRs produced in this way to be only associated with recent merger events, for example. On the other hand, also keep in mind that electrons lose energy so quickly that we can expect to see them only very close to where they have been accelerated or, in the case of secondary electrons, produced via decay of π^\pm . In the context of structure shocks, we then should find electronic emissions either in association with current shocks or as secondaries associated with the accumulated CR proton population and the thermal baryons. Synchrotron radiation depends sensitively on magnetic field strength, so those emissions will also be heavily weighted towards regions of the strongest fields, wherever they form.

3. Diffusive Shock Acceleration

The DSA paradigm depends on the ability of energetic charged particles to pass through the dissipative layer in a shock mostly unimpeded, but also on the existence of sufficiently strong scattering to cause the particles to propagate diffusively upstream and downstream of the shock with respect to the bulk flow. That requires a weak magnetic field, which may not exist in primordial matter. On the other hand the first stars, galaxies and perhaps shocks should have seeded the ICM with magnetic flux. Fields $\gtrsim 0.1 \mu\text{G}$ should be adequate to accelerate particles in structure shocks to very high energies on reasonable time scales (e.g., Kang et al 1996). If a shock is planar on the scale of the particle scattering lengths and involves a simple, sharp transition, then the classic “test particle” solution for the momentum distribution of energetic particles is a power

law, $f(p) \propto p^{-q}$, independent of any other details with a slope given by

$$q = \frac{3r}{r-1} \rightarrow \frac{4M^2}{M^2-1} \approx 4(1 + \frac{1}{M^2}), \quad (1)$$

where r is the compression ratio of the shock and the arrow corresponds to a $\gamma = \frac{5}{3}$ gas. This leads to the well-known behavior, $q \rightarrow 4$, in the strong shock limit.

For that spectral form the energy and pressure in this population diverge logarithmically as the momentum, $p \rightarrow \infty$, so it was recognized a long time ago that diffusive shock acceleration could in principle become quite efficient (e.g., Axford 1982). Already for $M = 3$, equation 1 gives $q = 4.5$, while for $M = 5$ the slope is $q = 4.17$. So, even moderate shocks can transfer substantial fractions of the kinetic energy flux into CRs if the seed population is adequate and the maximum energy is relativistic. The particle acceleration time scales with the diffusion time across the shock, $t_d = D/u_s^2$. Again employing a Bohm diffusion model we can estimate that the time to accelerate CRs to a PeV in a structure formation shock with speed $u_s \sim 10^3 \text{ km/sec}$ can be as little as $\sim 10^7 \text{ yr}$ when the magnetic field $\sim 1 \mu\text{G}$. The seed CR population can come from previous sources or particles injected at the shock from the thermal plasma. The latter process is not well understood, but is certainly nonlinear and probably depends on the orientation of the magnetic field. Within our current understanding injection is sometimes modeled as a “thermal leakage” in which a small fraction of the downstream thermalized population is successful in crossing the postshock turbulence and the shock itself back into the approaching plasma. From there it can be returned downstream with an energy boost factor $\sim u_s/c$ to begin the acceleration process. Theoretical models (e.g., Malkov 1998) and numerical simulations (Kang et al 2002) suggest that a simple way to model the injection physics is to match the thermal and isotropic nonthermal particle distributions at a particle speed that is several times the characteristic postshock thermal particle speed (Kang et al 2002), defining an “injection momentum”. In the simulations described below we will employ that model with injection momentum set to 2.6 times the postshock thermal peak. Further details can be found in Miniati 2001. This will generally lead to an injected fraction of CRs $\sim 10^{-4}$, consistent with more sophisticated numerical simulations of the diffusive shock acceleration process (Kang et al 2002).

We note as well with this level of CR injection that the acceleration efficiency of shocks with $M \sim 3-5$ should be on the order of 10-30% (e.g., Kang et al 2002). That estimate is obtained from nonlinear simulations of CR modified shocks that include feedback between the CR population, bulk flow upstream and downstream of the shock as well as the injection process itself. Still, this is sufficiently small that shock modifications due to CR pressure gradients are modest and the CR momentum distribution is not greatly modified from the test particle form. This is convenient, since it allows us to make reasonable estimates of CR properties in clusters using test particle models for acceleration.

4. Cosmological Simulations Including CR Acceleration at Shocks

4.1. Methods

A number of authors have explored analytically the acceleration of CRs by one or more processes (e.g., Kang et al 1996; Eilek & Wetherall 1999; Blasi 2000; Brunetti et al 2001) in clusters. Yet, given the complex histories of clusters, the absence of stationary structures and likely wide ranges of properties among individual clusters, numerical simulations offer a powerful alternative tool to gain a more complete picture. With this in mind we have carried out several structure formation simulations that incorporate an efficient numerical scheme for transport of CRs, including diffusive acceleration at shocks, as well as adiabatic losses for protons and radiative and Coulomb losses for electronic components. The scheme is Eulerian, uses a finite volume approach to advection in coordinate and momentum space, and models the momentum distribution as a piecewise power law function to allow a coarse momentum grid. To conserve computational effort the simulations described consider CRs only with energies below 1 PeV, so that we can reasonably assume acceleration at shocks is instantaneous compared to dynamical time steps and that spatial diffusion of CRs in smooth flows can be ignored. Dynamical feedback of CRs is neglected; that is, the CR population is treated in the test particle limit. Thus, CRs emerging from shocks take a spectral form governed by equation 1 for injected CRs or whenever that spectrum is flatter than the incident CR spectrum.

Electrons are split into a “primary” population derived from thermal leakage at shocks and a “secondary” population derived from π^\pm decays following inelastic p-p collisions. Those same collisions produce γ -rays via π^0 decay, and that distribution is also computed. Since injection of primary electrons at shocks is not well understood, we simply scale it as a fraction, $R_{e/p}$ of the proton injection described above. Using galactic CRs for a reference, we may expect $R_{e/p} \sim 0.01$. The proton, primary and secondary electron populations are all evolved separately. Our full numerical method is an extension of that described in Jones et al (1999) and has been explained in detail by Miniati (2001). The Eulerian cosmology code is the same as that employed in the simulation shown in Figure 1, and outlined in §2.

4.2. Some Results: CR Properties

Detailed discussions of results from these simulations can be found in Miniati et al (2001a,b) and Miniati (2002a,b). Here we mention briefly a few of the salient results, especially as they relate to themes of this meeting.

A single structure formation simulation leads to many clusters that have formed naturally from random initial fluctuations. While we pay a price in reduced resolution when we simulate a large volume, we gain an unbiased sample of objects whose properties can be explored from multiple perspectives. The simplest question we can ask from these simulations is an estimate of the total CR population we can expect. Figure 2 shows estimates of the fraction of individual cluster core pressures contributed by CR protons resulting from diffusive acceleration at structure shocks. These data were obtained from a “concordance model” Λ CDM simulation with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_B = 0.04$, $h = 0.67$ and $\sigma_8 = 0.9$ (Miniati 2002a,b). (Similar results were reported for an analogous

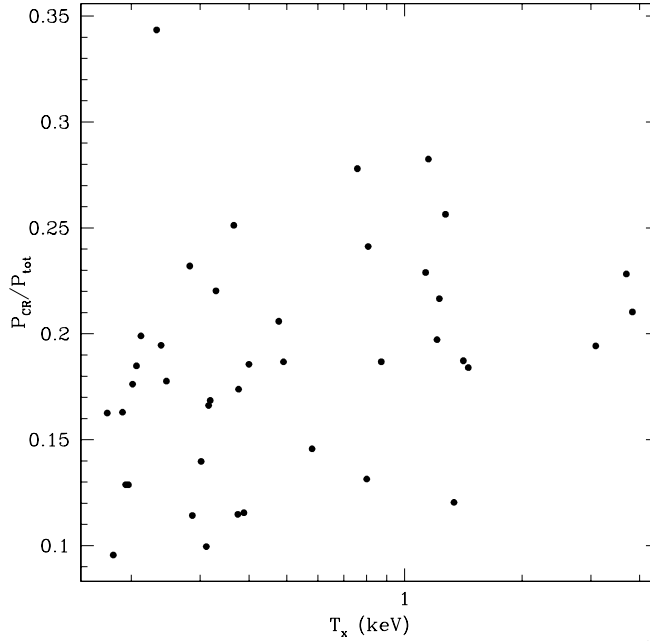


Figure 2. Fractional CR pressure in the central $0.5 h^{-1}$ Mpc of individual clusters as a function of cluster core temperature at $z = 0$ in a Λ CDM simulation as discussed in the text.

SCDM simulation, Miniati et al 2001a.) The simulation shown used a computational box $50 h^{-1}$ Mpc on a side in comoving coordinates with 512^3 grid zones and 256^3 dark matter particles.

The mean CR pressure contribution in these clusters is about 20% in the cores, but there is a very wide scatter. These are first estimates, since the model for diffusive CR acceleration was applied in the test particle limit and the injection rates are uncertain. Nonetheless, the numbers are consistent with expectations from more sophisticated nonlinear simulations of individual shocks in the range of Mach numbers mentioned earlier that are most important for heating of cluster ICMs. There is no clear trend of P_{CR}/P_{tot} with cluster temperature. The scatter seen in Figure 2 is real and reflects the influence of varied shock histories among individual clusters. We emphasize again that P_{CR} depends on the time integrated shock history of the plasma in a cluster rather than a single event, such as a recent merger.

Reflecting that fact, inspection of the spatial distribution of CR protons in the simulations shows them to be distributed roughly similar to the thermal plasma (Miniati et al 2001a). However, since the CRs are continuously injected at accretion shocks, which lie mostly outside cluster cores, the CR distributions are broader than the X-ray emitting thermal gas. From these behaviors we can immediately anticipate a key property of secondary electron CRs as well as associated γ -rays from π^0 decays. Both will be concentrated in cluster cores, since they will result from a convolution of CR and thermal proton distributions. That is distinctly different from the distribution of primary CR electrons and their emissions, which are concentrated close to contemporary shocks. This last

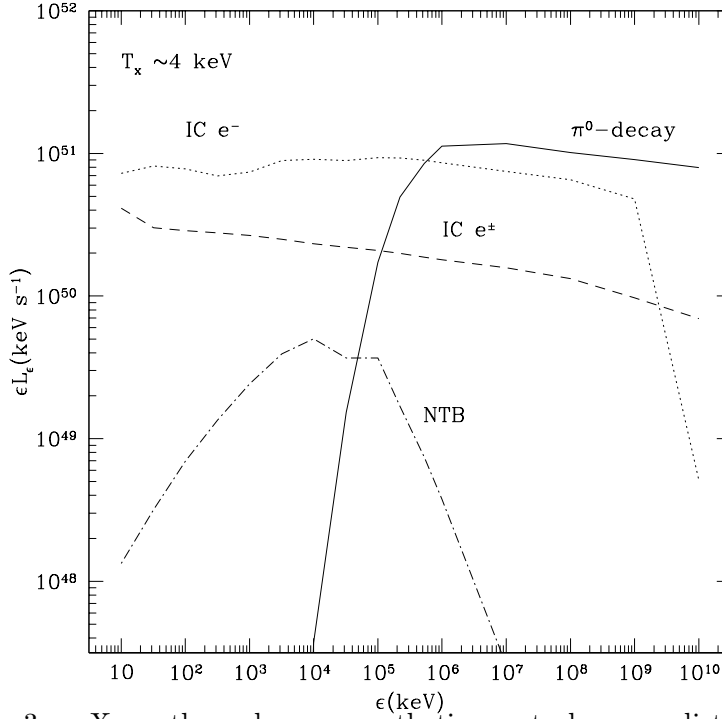


Figure 3. X-ray through γ -ray synthetic spectral energy distribution for a simulated cluster (adapted from Miniati 2002b).

point was mentioned earlier and comes from the very short energy loss time scales of electrons. While shocks can and do penetrate into cluster cores, they are more common, stronger and perhaps more obvious outside the cores.

4.3. Some Results: Nonthermal Emissions

The spatial and momentum distributions of the CRs can be used to compute expected emissions from such processes as inverse-Compton scattering of the CMB, bremsstrahlung and, since our simulations also include passive magnetic fields, synchrotron radio emissions. From inelastic p-p scattering products we include emissions from secondary e^\pm and γ s from π^0 decay, as well.

Since there has been much recent discussion about nonthermal X-rays and γ -rays from clusters, we focus our attentions there. If the primary electron to proton ratio in cluster CRs is similar to that in galactic CRs, so that primary electrons constitute something like a percent of the total primary CRs, then the average γ -ray luminosities in our simulated clusters are produced in comparable measure by inverse-Compton emission from primary electrons and π^0 decay. The primary electron inverse-Compton contribution is especially important in extended regions outside cluster cores, where strong shocks are most likely, while π^0 decays can dominate at high energies in cluster cores.

Figure 3 illustrates the X-ray to γ -ray spectral energy distribution computed from one $T_x \sim 4$ keV cluster in the simulation of Miniati (2002a,b). IC emission of primary and secondary electrons (actually e^\pm), nonthermal bremsstrahlung and γ -rays from π^0 decay are included. The emissions were integrated inside a spherical volume of radius $5 h^{-1}$ Mpc.

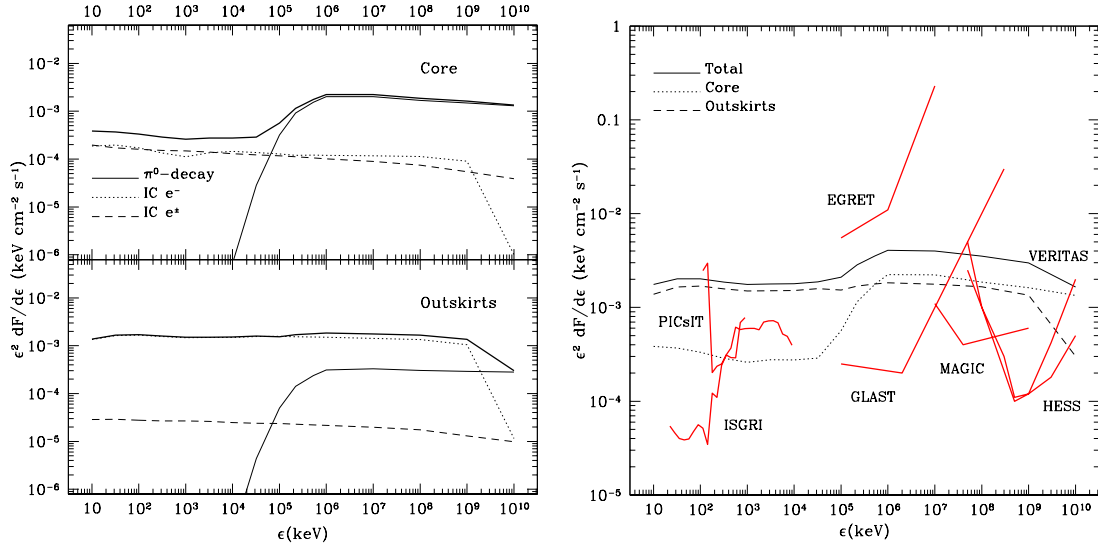


Figure 4. Left: Spectral energy distributions from the core (top) and the outskirts (bottom) of the cluster illustrated in Fig. 3 when the cluster is placed at a distance of 105 Mpc. The heavy solid lines show the totals in each region. Right: Total flux compared to various γ -ray instrument detection limits. (adapted from Miniati 2002b).

Primary electron inverse-Compton and π^0 emissions dominate as mentioned, while nonthermal bremsstrahlung is largely unimportant. Note at high energies that the spectra of inverse-Compton emissions from both electronic components and π^0 -decay γ s are similar over a substantial range. All reflect the spectra of primary protons, with adjustments for radiative losses in the electrons and for pion generation and decay cross sections in the other case. Below a GeV, however, the π^0 contribution drops due to production threshold and phase space limits, while above a few TeV the primary electron spectrum cuts off since electron energy loss rates dominate DSA acceleration rates.

Examination of the spatial distributions of emissions of the different contributions uncovers some important details of how structure shocks may reveal themselves, and suggests some strategies for testing models for particle acceleration. Figure 4 separates the emissions from the clusters shown in Figure 3 into contributions from the cluster core (2 Mpc diameter) and from the “outskirts” defined as an annulus between 1 Mpc and 3 Mpc radius. For this plot the cluster was assumed to be at the distance of the Coma cluster, taken as $d = 105$ Mpc. The figure illustrates how emissions associated with secondary CRs products concentrate towards cluster cores, while emissions from the outer regions are dominated by primary electrons. Spectral distributions are distinctly different in the two cases, so it should be possible in principle to identify emissions from the hadronic CR component in the cluster cores. That observational challenge is also currently underway in efforts to establish the hadronic CR population in galactic supernova remnants (e.g., Aharonian et al 1994). The right panel in the figure shows the integrated flux from the different parts of the selected cluster in comparison to various detection limits.

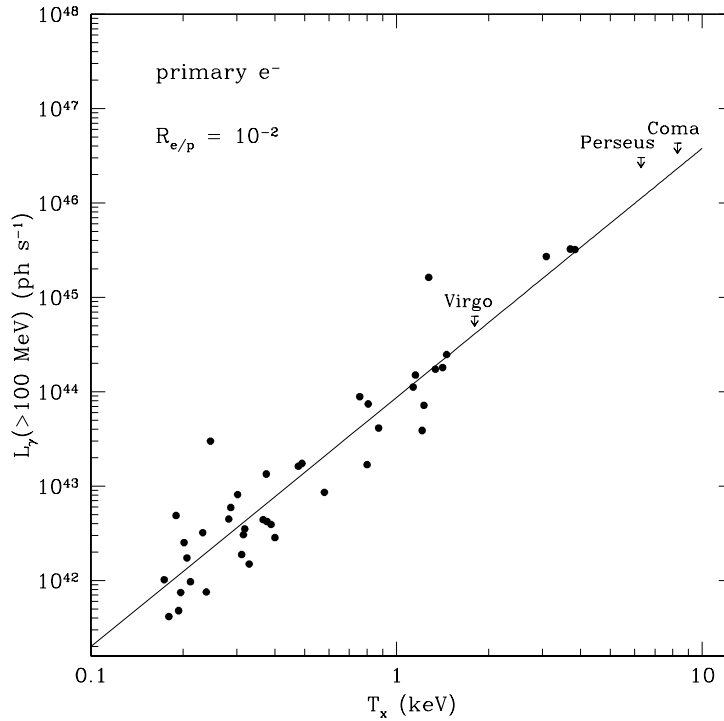


Figure 5. Inverse-Compton γ -ray luminosity above 100 MeV from individual clusters as a function of the cluster core temperature (from Miniati 2002a).

The above discussion also is relevant to our ability to understand the origins of diffuse radio halos and relic sources. Recall that the former are found primarily in cluster cores, while the latter tend to lie in cluster outskirts. In our simulations core regions do emit synchrotron emissions that are produced mostly by secondary electrons. As discussed in Miniati et al 2001b the radio luminosities and polarization properties are similar to observed halos, and the radio luminosity is a very steep function of cluster temperature, consistent with the comparative rarity of observed halos. The main handicap in trying to explain radio halos entirely in terms of secondary decay products is that this explanation does not appear to explain naturally observations of radio spectral steepening (e.g., Deiss et al 1997). However, more sophisticated models including other contributions to the electron population or its acceleration might solve this problem. The other issue sometimes raised for secondary electron radio halo models is whether the required electron population is consistent with limits to the inverse-Compton X-ray and γ -ray fluxes in Coma, for example. For very weak fields the inverse-Compton flux from the electron population required to account for radio halo in Coma would become excessive (Blasi & Colafrancesco 1999; Miniati et al 2001a). On the other hand if the magnetic field is in excess of a few μG the required electron population to explain the synchrotron source is reduced to a level leading to inverse-Compton luminosities consistent with current limits on the γ -ray flux, and below the expected π^0 flux at high energies, in fact.

The simulations also produce diffuse radio sources resembling radio relics in some of the same outer regions where the inverse-Compton emissions from primary electrons are prominent (Miniati et al 2001b). These are immediate postshock volumes where primary electrons still remain energetic and where magnetic fields are relatively strong. The simulations predict that these regions should be highly polarized, since the local magnetic fields tend to become aligned with the shock faces. These properties all seem consistent with those seen in radio relic sources.

Finally we illustrate in Figure 5 the individual inverse-Compton γ -ray luminosities from primary accelerated electrons computed in a Λ CDM simulation of Miniati (2002a,b). The solid line is a least squares power law fit to the simulation data, which has a slope 2.6, in agreement with what is expected from cluster scaling relations (Miniati 2002a). The simulated cluster luminosities were integrated inside a $5 h^{-1}$ Mpc radius spherical volume. For the illustration a relative electron shock injection rate of $R_{e/p} = 0.01$ was used. Computed fluxes scale directly with that parameter. Several EGRET upper limits for nearby clusters are shown in the figure for comparison. The estimated luminosities from the simulations are consistent with the current γ -ray non-detections of clusters, but they also suggest that γ -ray fluxes may be large enough to be seen by the next generation of experiments.

5. Summary

Shocks are a ubiquitous consequence of cosmic structure formation, and they play an essential role in heating of cluster media. Virtually all of the gas in cluster media has been processed by at one or more shocks of at least moderate strength. Since these shocks involve highly tenuous ionized media, they are collisionless in nature, so will not fully thermalize the plasmas passing through them. One likely consequence is the acceleration of relativistic particles, or cosmic rays. We have begun to explore through numerical simulations the roles that particle acceleration in structure shocks may play. Our current conclusions are:

- The shocks that are primarily responsible for heating cluster ICMs can be efficient particle accelerators, possibly generating nonthermal proton pressures on the order of 10% or more of the total virial pressure in cluster cores.
- Cluster ICMs are very good reservoirs for energetic protons, so the cosmic ray populations there reflect the full history of the cluster medium more than any single event, such as a recent merger.
- Relativistic electrons at most energies have loss lifetimes so short that they must either be accelerated locally or be secondary products from energetic hadronic cosmic rays in order to have populations great enough to account for detectable nonthermal emissions.
- There are two main regions for production of nonthermal radiation in clusters; the X-ray bright core and the outskirts where strong shocks are most likely.
- Inverse-Compton emission and π^0 decays dominate the production of γ -rays in typical clusters. Inverse-Compton from primary electrons dominates in the outskirts, provided electrons are injected in proportion to ions comparably

to the galactic cosmic rays; that is, so that a fraction of a percent of the energy flux through shocks is transferred to electrons.

- In cluster cores γ -ray emission above a few hundred MeV should be dominated by π^0 decays, whereas inverse-Compton emission from secondary electrons dominates in these regions at lower γ -ray energies.

- Primary and secondary electrons may also contribute substantially to non-thermal radio synchrotron emissions in clusters. Primary electron emissions are confined to volumes close to contemporary shocks, so should be seen mostly in cluster outskirts, contributing to radio relic sources. Secondary electronic emissions should again be concentrated in cluster cores, contributing to radio halos.

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